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DESCRIPTION

BALL-AND-ROLLER BEARING

TECHNICAL FIELD

The present invention relates to ball-and-roller bearings for use in such applications as decelerators, drive pinions, and transmissions, and more particularly to a ball-and-roller bearing that has a long rolling fatigue life and is highly resistant to cracking and dimensional change over time.

BACKGROUND ART

Bearing parts are often treated with heat to extend their rolling fatigue life. In some cases, bearing parts are heated in an atmosphere of an RX gas mixed with gaseous ammonia to form a carbonitrided surface layer (See, for example, Japanese unexamined Patent Publications H08-4774 and H11-101247). Not only can this carbonitriding process form a hard surface layer, but it can also lead to the formation of retained austenite in the microstructure, increasing the rolling fatigue life of the bearing parts.

Since the carbonitriding process is based on the principle of diffusion, the environment of the process must

ATTACHMENT B

be kept at high temperature for a prolonged time period. As a result, the microstructure of the steel tends to become coarse, which makes it difficult to increase the crack resistance. This problem must be addressed, as well as the problem of the increased dimensional change over time caused by the increase in the amount of retained austenite.

One way to ensure long rolling fatigue life while increasing the crack resistance and preventing the increase in the dimensional change over time is by alloy design. However, this approach leads to an increased cost due to expensive materials.

To meet the requirements of high-load, high-temperature operation environment, future bearing parts are expected to withstand higher loads and higher temperatures than ever before. To this end, bearing parts are needed that have long rolling fatigue life, high crack resistance, and high dimensional stability.

DISCLOSURE OF THE INVENTION

It is an object of the present invention to provide a ball-and-roller bearing that has high crack resistance and high dimensional stability and at the same time has long rolling fatigue life even in a high-temperature environment.

A ball-and-roller bearing according to the present invention includes an inner ring, an outer ring, and a plurality of rolling elements. This ball bearing is characterized in that at least one of the inner ring, the outer ring and the rolling elements is adapted to high temperature environment, is formed of a steel alloyed with 0.6% to 1.3% by weight of C (carbon), 0.3% to 3.0% by weight of Si (silicon), 0.2% to 1.5% by weight of Mn (manganese), 0.03% by weight or less of P (phosphorus), 0.03% by weight or less of S (sulfur), 0.3% to 5.0% by weight of Cr (chromium), 0.1% to 3.0% by weight of Ni (Nickel), 0.050% by weight or less of Al (aluminum), 0.003% by weight or less of Ti (titanium), 0.0015% by weight or less of O (oxygen), and 0.015% by weight or less of N (nitrogen) with the remainder being made up of Fe (iron) and inevitable impurities, and has a nitrogen-enriched layer formed thereon; and the austenite crystals of the steel have a grain size number of greater than 10. In the course of our studies, the present inventors have found an optimum combination and respective contents of elements for making parts of ball-and-roller bearings for use in high temperature environment. The ball-and-roller bearings with their parts made of a steel having such composition are inexpensive and have an increased rolling fatigue life when used in an environment where they are exposed to high temperatures and foreign particles. Hereinafter, the reasons for determining the amount of each chemical component will be described:

(1) C content (0.6% to 1.5%)

Carbon is an essential element to ensure the strength required for ball-and-roller bearings and must be present in an amount of 0.6% or more to achieve the desired hardness after heat treatment. Thus, we determined the lower limit of the C content to be 0.6%. As will be later described, carbides are important factors in determining the rolling fatigue life of bearings. It has been demonstrated that if C content is greater than 1.3%, then large carbide clusters are formed, resulting in a decrease in the rolling fatigue life. Thus, we determined the upper limit of the C content to be 1.3%.

(2) Si content (0.3% to 3.0%)

Silicon is preferably added for its ability to prevent the softening of the steel at higher temperatures and thereby improve the heat resistance of the ball-and-roller bearings. The lower limit of the Si content was determined to be 0.3% since the advantageous effect would not be achieved if the element is present in lesser amounts. As long as the amount of Si is 3.0% or less, the heat resistance of the steel is increased as the amount of Si is increased: The heat resistance is no longer improved, but rather the workability during hot working is decreased and the steel becomes difficult to machine if the amount of Si exceeds 3.0%. Thus, we determined the upper limit of the Si

content to be 3.0%.

(3) Mn content (0.2% to 1.5%)

Manganese, an element used in the deacidification process during the production of steel and used to improve quenchability of steel, must be added in amounts of 0.2% or more to achieve the desired effect. Thus, the lower limit of the Mn content was determined to be 0.2%. Conversely, Mn present in amounts greater than 1.5% makes the steel difficult to machine. Thus, the upper limit of the Mn content was determined to be 1.5%.

(4) P content (0.03% or less)

Phosphorus segregates to the austenite grain boundaries to cause a decrease in the toughness or the rolling fatigue life. Thus, the upper limit of the P content was determined to be 0.03%.

(5) S content (0.03% or less)

Sulfur affects the workability of steel during hot working and forms nonmetallic inclusions in steel to cause a decrease in the toughness or the rolling fatigue life of steel. Thus, we determined the upper limit of the S content to be 0.03%. Despite these adverse effects, the presence of sulfur makes the steel easy to machine to a degree. Thus, the presence of sulfur is acceptable if the amount is 0.005% or less, though the element is desirably eliminated as much

as possible.

(5) Cr content (0.3% to 5.0%)

Chromium has a significant importance to the present invention: It is added to steel for the purposes of improving quenchability, ensuring the hardness caused by carbides, and extending steel life. The element has to be added in amounts of 0.3% or greater to obtain desired carbides. Thus, we determined the lower limit of the Cr content to be 0.3%. Conversely, chromium causes formation of clusters of carbides and thus reduces the rolling fatigue life when present in amounts greater than 5.0%. Thus, the upper limit of the Cr content was determined to be 5.0%.

(7) Al content (0.050% or less)

While aluminum is used as a deacidifying agent during the production of steel, it is desirably eliminated as much as possible since it forms hard oxide inclusions that cause a decrease in the rolling fatigue life. We determined the upper limit of the Al content to be 0.050% since a significant decrease in the rolling fatigue life was observed when Al was present in greater amounts.

The lower limit of the Al content is preferably set at 0.005% since decreasing Al to less than 0.005% leads to an increase in the production cost of the steel.

(8) Ti content (0.003% or less), O content (0.0015% or less), and N content (0.015% or less)

Titanium, oxygen, and nitrogen form oxides and nitrides in steel as nonmetallic inclusions where fatigue breakage starts, thereby decreasing the rolling fatigue life. Thus, the upper limits of the Ti, O and N contents were determined to be 0.03%, 0.0015% and 0.015%, respectively.

(9) Ni content (0.1% to 3.0%)

Nickel has a significant importance to the present invention: It prevents the structural change in steel especially when the bearings are operated in a high temperature environment and subjected to rolling fatigue. The element suppresses the decrease in the hardness at higher temperatures and thereby improves the rolling fatigue life. Moreover, Ni serves to increase the toughness and improve life of bearings when the bearings are used in environments where they are exposed to foreign particles. The element also increases the corrosion resistance. We determined the lower limit of the Ni content to be 0.1% since the desired advantages are not achieved if the element is present in lesser amounts. Conversely, nickel when present in amounts greater than 3.0% causes formation of significant amount of retained austenite during quenching, leading to failure to achieve desired hardness. Too much nickel also leads to increased cost of steel. Thus, the upper limit of the Ni content was determined to be 3.0%.

The above-described steel may further contain at least one of Mo and V. The amount of Mo is preferably 0.05% or more and less than 0.25% by weight and the amount of V is preferably 0.05% to 1.0% by weight. These elements can further improve the rolling fatigue life of bearings in an environment where bearings are exposed to high temperatures and foreign particles. Mo and V also serve to increase the hardness after tempering. The amount of each chemical component described above is determined for the following reasons:

(10) Mo content (0.05% or more and less than 0.25%)

Molybdenum serves to improve quenchability of steel and prevent the softening of steel during tempering when solved in carbides. It is added to steel because of its ability to improve the rolling fatigue life at high temperatures. If the Mo content is 0.25% or more, not only is the cost of steel increased, but also, the hardness of steel does not decrease during the softening process to facilitate machining, resulting in a significantly decrease in the machinability of the steel. Thus, the upper limit of the Mo content was determined to be less than 0.25%. If contained in amounts less than 0.05%, Mo does not help formation of carbides. Thus, the lower limit of the Mo content was determined to be 0.05%.

(11) V content (0.05% to 1.0%)

Vanadium binds to carbon and crystallizes as fine carbides. This facilitates formation of fine crystal grains and thus improves the strength and toughness of steel. Moreover, the presence of V increases the heat resistance of steel, prevents the softening after tempering at a high temperature, improves the rolling fatigue life, and decreases the deviation of life. These effects are achieved only when the element is present in amounts of 0.05% or more. Thus, we determined the lower limit of the V content to be 0.05%. Conversely, V present in amounts greater than 1.0% causes a decrease in the machinability and workability during hot working. Thus, the upper limit of the V content was determined to be 1.0%.

The nitrogen-enriched layer is a layer formed on the surface of the bearing rings (inner and outer rings) or the rolling elements and containing an increased amount of nitrogen. The layer can be formed by such processes as carbonitriding and nitriding and preferably has a nitrogen content of 0.1% to 0.7%. If the amount of nitrogen is less than 0.1%, the desired effect may not be obtained. In particular, the rolling life of the bearings is decreased in an environment where bearings are exposed to foreign particles. Conversely, nitrogen present in amounts greater than 0.7% causes formation of voids and leads to formation of excessive retained austenite. As a result, the desired

hardness cannot be achieved and the life of bearings is shortened. In cases of the nitrogen-enriched layer formed on the bearing rings, the nitrogen content is measured on the machined ring surface at a depth of 50 μm using, for example, an electron probe microanalyzer (EPMA).

When the austenite crystals have a small particles size with a grain size number of greater than 10, the bearings have a significantly increased rolling fatigue life. If the grain size number of the austenite crystals is 10 or smaller, the rolling fatigue life is not significantly increased. Thus, steel with the austenite crystals having a grain size number of greater than 10, typically 11, is used in the present invention. While it is preferred that austenite have a finer grain size, it is generally difficult to obtain austenite with a grain size number of greater than 13. Since the grain size of austenite is the same in the carbonitrided surface layer of the bearing parts and inside the carbonitrided surface layer, the above-described crystal grain size applies not only to the surface, but also to the interior of the bearing parts.

The nitrogen-enriched layer and the austenite structure with a grain size number of 11 or greater together help improve the rolling fatigue life and the crack resistance of the ball-and-roller bearing of the present invention and make the bearing parts less susceptible to

dimensional change over time.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic cross-sectional view of a ball-and-roller bearing in one embodiment of the present invention.

Fig. 2 is a diagram illustrating a heat treatment process of the ball-and-roller bearing in one embodiment of the present invention.

Fig. 3 is a diagram illustrating a variation of the heat treatment process of the ball-and-roller bearing in one embodiment of the present invention.

Fig. 4A is a photograph showing microstructure, in particular austenite grains of a bearing part in one example of the present invention.

Fig. 4B is a photograph showing microstructure, in particular austenite grains of a conventional bearing part.

Fig. 5A is a schematic of austenite grain boundaries of Fig. 4A.

Fig. 5B is a schematic of austenite grain boundaries of Fig. 4B.

Fig. 6 is a diagram showing a test piece for the static collapse test (for the measurement of fracture stress).

Fig. 7A is a schematic front view of a rolling fatigue life tester.

Fig. 7B is a schematic side view of the rolling fatigue life tester

Fig. 8 is a test piece for the static fracture toughness test.

BEST MODE FOR CARRYING OUT THE INVENTION

One embodiment of the present invention will now be described with reference to the accompanying drawings. Fig. 1 is a schematic cross-sectional view of a ball-and-roller bearing in one embodiment of the present invention. In Fig. 1, the ball-and-roller bearing 10 principally includes an outer ring 1, an inner ring 2, and a plurality of rolling elements 3. While a radial ball bearing is shown in the figure, ball bearings, conical roller bearings, cylindrical roller bearings, and needle-shaped roller bearings are also subjects of the present invention. The rolling elements 3 are rollably held by a cage arranged between the outer ring 1 and the inner ring 2. At least one of these bearing parts--the outer ring 1, the inner ring 2, and the roller elements 3--has a nitrogen-enriched layer.

As a specific example of the process to form the nitrogen-enriched layer, heat treatments, such as carbonitriding, are now described. Fig. 2 illustrates a heat treatment technique for ball-and-roller bearings according to the present invention and Fig. 3 illustrates its

variation. Fig. 2 shows a heat treatment pattern involving primary and secondary quenching steps, whereas Fig. 3 shows another heat treatment pattern in which the material is cooled below the A_1 transformation point during quenching and is subsequently reheated and then quenched at the end of the process. During the treatment T_1 shown in these figures, steel is sufficiently carburized while carbon and nitrogen are diffused in it. Then, the steel is cooled below the A_1 transformation point. During the subsequent treatment T_2, the steel is reheated to a temperature above or equal to the A_1 transformation point and below the treatment temperature T_1 and is then quenched in oil.

Unlike the conventional heat treatment including carbonitriding followed by quenching one time, these heat treatments can increase the crack resistance while allowing formation of a carbonitrided surface layer, thereby decreasing the dimensional change over time. According to the heat treatment techniques for ball-and-roll bearings of the present invention shown in Figs. 2 and 3, a microstructure can be obtained in which the size of the austenite crystal grains is less than half of the grains formed in bearing parts subjected to conventional heat treatments. The bearing parts subjected to the above-described heat treatments have long rolling fatigue life and high crack resistance and undergo less dimensional change over time. The bearing parts may be tempered to a high

temperature of 350°C for particular applications.

Fig. 4 contains photographs of microstructure, in particular austenite grains of bearing parts with Fig. 4A being of a bearing part of the present invention and Fig. 4B being of a conventional bearing part. Specifically, Fig. 4A shows the grain size of austenite crystals in a bearing steel that has been subjected to the heat treatment in accordance with the pattern described with reference to Fig. 2. For comparison, Fig. 4B shows the grain size of austenite crystals in a bearing steel that has been subjected to the conventional heat treatment. Figs. 5A and 5B are schematics of Figs. 4A and 4B, respectively, showing the grain size of austenite crystals. It is seen that the austenite formed by the conventional heat treatment has a grain size number of 10 according to JIS standard, whereas the austenite formed by the heat treatment of the present invention has a finer grain size number of 12. Using the section method, the average grain size of the grains shown in Fig. 4A was determined to be 5.6 μm.

Examples of the present invention will now be described.

(Example I)

A steel alloyed with 1.2wt% C, 1.0wt% Si, 0.5wt% Mn, 1.0wt% Ni and 1.5wt% Cr was analyzed for the following: (1)

hydrogen level, (2) crystal grain size, (3) Charpy impact test, (4) fracture stress, and (5) rolling fatigue test. The results are shown in Table 1.

(Table 1)

Samples	A	B	C	D	E	F	Conventional carbonitriding	Normal quenching
Secondary quenching temperature (°C)	780	800	815	830	850	870	-	-
Hydrogen level (ppm)	-	0.43	0.45	0.42	0.39	0.44	0.83	0.40
Crystal grain size (JIS)	-	12	11	11	10	9	9	9
Charpy impact (J/cm^2)	-	6.80	6.55	6.35	6.20	6.15	5.10	6.40
Fracture stress (MPa)	-	2800	2750	2630	2630	2600	2080	2750
Rolling fatigue life ratio (L_{10})	-	2.3	2.5	2.4	1.6	1.5	1.4	1

The samples were prepared as follows:

Samples A through D (Samples of the present invention): Carbonitriding was carried out at 850°C for 150min in a mixed atmosphere of RX gas and gaseous ammonia. During the heat treatment in accordance with the pattern shown in Fig. 2, the samples were carbonitrided at 850°C and were quenched (Primary quenching). Subsequently, the samples were heated to a temperature lower than the carbonitriding temperature (780°C to 830°C, Secondary quenching). Sample A, which was heated at 780°C during the secondary quenching

step, did not achieve sufficient hardness and was excluded from the test.

Samples E and F (Comparative Examples): Carbonitriding was carried out in the same manner as in the production of Samples A through D of the present invention. The secondary quenching was carried out at a temperature higher than or equal to 850°C of the carbonitriding temperature (850°C to 870°C).

Sample carbonitrided in a conventional manner (Comparative Example): Carbonitriding was carried out at 850°C for 150min in a mixed atmosphere of RX gas and gaseous ammonia. The sample was carbonitrided and was directly quenched. Secondary quenching was not performed.

Normally quenched sample (Comparative Example): The sample was heated at 850°C and quenched without carbonitriding. Secondary quenching was not performed.

These samples were tempered at 180°C for 120min.

Next, the method for testing will be described.

(1) Hydrogen level

The amount of non-diffused hydrogen present in steel was analyzed using a DH-103 hydrogen analyzer (LECO). The

amount of diffused hydrogen was not measured. The specifications of the DH-103 hydrogen analyzer (LECO) are as follows:

Range: 0.01 to 50.00 ppm

Accuracy: ±0.1 ppm or ±3% H (greater of the two)

Sensitivity: 0.01 ppm

Detection principle: Heat conduction

Sample weight and size: 10 mg to 35 mg (Maximum: 12mm diameter x 100mm length)

Furnace temperature range: 50°C to 1100°C

Reagents: Anhydrone $Mg(ClO_4)_2$, Ascarite NaOH

Carrier gas: Gaseous nitrogen, gas-dosing gas: hydrogen gas. Each gas has a purity of 99.99% or higher and a pressure of 40 psi (2.8 kgf/cm^2).

Briefly, the procedure is performed as follows: A sample collected in a special sampler is placed in the hydrogen analyzer. The diffused hydrogen inside is introduced to a heat conduction detector by a nitrogen carrier gas. The diffused hydrogen is not analyzed in this example. The sample is removed from the sampler and is heated in a resistor furnace. The non-diffused hydrogen is introduced to the heat conduction detector by a nitrogen carrier gas. The heat conductivity is measured in the heat conduction detector as a measure of the amount of non-diffused hydrogen.

(2) Crystal grain size

The crystal grain size was determined by the procedure according to the grain size test for austenite crystals in steel as specified by JIS G 0551.

(3) Charpy impact test

Charpy impact test was performed based on the procedure of the Charpy impact test for metallic materials as specified by JIS Z 2202. Sample pieces used were U-notched sample piece (JIS sample piece No. 3).

(4) Fracture stress

Fig. 6 shows a sample piece for the static fracture strength test (to determine fracture stress). A load applied in the direction P is monitored until the sample is fractured. The load at which the sample fractures is then converted by the following stress equation for curved beam into a stress value. Sample pieces having a different shape from the sample piece shown in Fig. 6 may also be used.

Given that σ_1 is the fiber stress at the protruded surface of the sample piece and σ_2 is the fiber stress at the recessed surface of the sample piece, σ_1 and σ_2 are given by the following equations (Handbook of Mechanical Engineering A4, Material Dynamics A4-40). In the following equations, N is the axial force that acts in the cross-section containing

the axis of the annular test piece, A is the transverse cross-sectional area, e_1 is the outer diameter, e_2 is the inner diameter, and κ is the section modulus of curved beam.

$$\sigma_1 = (N/A) + \{M/(A\rho_0)\}[1 + e_1/\{\kappa(\rho_0 + e_1)\}]$$

$$\sigma_2 = (N/A) + \{M/(A\rho_0)\}[1 - e_2/\{\kappa(\rho_0 - e_2)\}]$$

$$\kappa = -(1/A)\int A\{\eta/\rho_0 + \eta\}dA$$

(5) Rolling fatigue life

Conditions for the test for rolling fatigue life are shown in Table 2. A rolling fatigue life tester is schematically shown in Fig. 7 in a planar view in Fig. 7A and in a side view in Fig. 7B. In Figs. 7A and 7B, a test piece 21 to be analyzed for the rolling fatigue life is driven by a drive roll 11 and is rotated while in contact with balls 13. Each ball 13 is 3/4 inch in diameter and is guided by guide rolls 12, so that it rolls as it exerts high surface pressure upon the test piece 21.

The results shown in Table 1 can be interpreted as follows.

(1) Hydrogen level

The sample carbonitrided by the conventional technique shows a high hydrogen level of 0.83 ppm. This is thought to be because ammonia (NH_3) present in the carbonitriding atmosphere has decomposed and the resulting hydrogen has

penetrated into steel. As opposed, Samples B through D each have a hydrogen level of 0.42 to 0.45 ppm, nearly half that of the sample carbonitrided by the conventional technique. This is comparable to the hydrogen level in the normally quenched sample.

The decrease in the hydrogen level helps prevent the steel from becoming brittle due to the dissolved hydrogen. Specifically, the decrease in the hydrogen level has led to a significantly increase in the Charpy impact in each of the Samples B through D.

(2) Crystal grain size

The crystal grain size is significantly small, that is, crystal grain number = 11 to 12, in each of Samples B through D, for which the temperature for the secondary quenching was lower than the temperature for the quenching during carbonitriding (Primary quenching). The austenite grains have a crystal grain size number of 9 and are more coarse in each of Samples E and F, the conventionally carbonitrided sample and the normally quenched sample than in Samples B through D of the present invention.

(3) Charpy impact test

As shown in Table 1, each of Samples B through D of the present invention has a Charpy impact of 6.35 to 6.80 J/cm^2, a significantly higher value than that of the

conventionally carbonitrided sample (5.10 J/cm^2). A sample for which the temperature for the secondary quenching is lower tends to have a higher Charpy impact. The normally quenched sample has a high Charpy impact of 6.40 J/cm^2.

(4) Fracture stress

The fracture stress is equivalent to crack resistance. According to Table 1, the conventionally carbonitrided sample has a fracture stress of 2080 MPa. In comparison, each of Samples B through D has an increased fracture stress of 2630 to 2800 MPa. The normally quenched sample has a fracture stress of 2750 MPa. These results indicate that the increased crack resistance of Samples B through D is largely attributable to the decrease in the hydrogen level, as well as to the finer austenite crystal grains.

(5) Rolling fatigue test

Table 1 indicates that the normally quenched sample has the shortest rolling fatigue life L_{10} due to no carbonitrided surface layer provided thereon, whereas the conventionally carbonitrided sample has a 1.4 times longer life. Samples B through D each have a significantly increased rolling fatigue life as compared to the conventionally carbonitrided sample. Samples E and F each has a rolling fatigue life comparable to the conventionally carbonitrided sample.

Collectively, these observations indicate that Samples B through D of the present invention each have a reduced hydrogen level, have finer austenite crystal grains with a grain size number of 11 or higher, and are improved in terms of Charpy impact, crack resistance, and rolling fatigue life.

(Example II)

Next, Example II will be described. The following articles X, Y, and Z were tested for the different properties. The same material (with 1.2wt% C, 1.0wt% Si, 0.5wt% Mn, 1.0wt% Ni and 1.5wt% Cr) was subjected to different heat treatments to make the articles X, Y and Z, as follows:

Article X (Comparative Example): Normal quenching only (without carbonitriding);

Article Y (Comparative Example): Carbonitriding followed by quenching (Conventional carbonitriding hardening). The article was carbonitrided at 845°C for 150min in a mixed atmosphere of RX gas and gaseous ammonium; and

Article Z (Example of present invention): A bearing steel was subjected to the heat treatment in accordance with the pattern shown in Fig. 2. The article was carbonitrided at 845°C for 150min in a mixed atmosphere of RX gas, followed by the final quenching at 800°C.

(1) Rolling fatigue life

The articles were tested for the rolling fatigue life using the condition and testing instrument as shown in Table 2 and Fig. 7. The results of the rolling fatigue life test are shown in Table 3.

(Table 2)

Sample piece	ϕ12 X L22 cylindrical sample piece
Test number	10
Steel ball used	3/4 inches (19.05 mm)
Contact surface pressure	5.88 GPa
Load speed	46240 cpm
Lubricant oil	Turbine VG 68 Forcible circulation

(Table 3)

Materials	Life (number of times load is applied)		Ratio of L_{10}
	L_{10} (x 10^4 times)	L_{50} (x 10^4 times)	
Article X	39800	69500	1.0
Article Y	59400	73200	1.5
Article Z	88900	103500	2.5

According to Table 3, Article Y of Comparative Example has a rolling fatigue life L_{10} (at which 1 out of 10 sample pieces breaks) that is 1.5 times longer than the normally quenched Article X of Comparative Example, indicating that the rolling fatigue life can be significantly increased by carbonitriding. In comparison, the rolling fatigue life of Article Z of the present invention is 1.5 times longer than that of Article Y and 2.2 times longer than that of Article X. The principal cause of this improvement is considered to be the fine microstructure of Article Z.

(2) Charpy impact test

The articles were tested for Charpy impact using U-notched sample pieces according to the above-described JIS Z 2242 standard. The results are shown in Table 4.

(Table 4)

Materials	Charpy impact (J/cm^2)	Ratio of impact
Article X	6.4	1.0
Article Y	5.2	0.8
Article Z	6.8	1.1

As shown, the carbonitrided Article Y (Comparative Example) has a lower Charpy impact than the normally hardened Article X (Comparative Example). Article Z has a comparable or higher Charpy impact than Article X.

(3) Static fracture toughness test

Fig. 8 shows a sample piece for static fracture toughness test. An approximately 1mm slit was formed in the notch of the sample piece and a static load was applied to the sample piece while it is supported at three points. The load P at which the sample fractured was determined. The fracture toughness (K_1c value) was calculated by the following equation (I). The results are shown in Table 5.

$$K_1c = (PL\sqrt{a}/BW^2)\{5.8 - 9.2(a/W) + 43.6(a/W)^2 - 75.3(a/W)^3 + 77.5(a/W)^4\} \qquad (1)$$

(Table 5)

Materials	Test number	K_1c ($MPa\sqrt{m}$)	Ratio of K_1c

Article X	3	17.2	1.0
Article Y	3	17.0	1.0
Article Z	3	19.5	1.1

Since the slit was formed to a greater depth than the carbonitriding layer, no significant difference was observed between Articles X and Y. Article Z of the present invention had a 1.1 times higher fracture toughness than Comparative Examples.

(4) Static collapse toughness test

Test pieces as shown in Fig. 6 were tested for static collapse toughness. A load was applied in the direction P shown in the figure to determine the static collapse toughness. The results are shown in Table 6.

(Table 6)

Materials	Test number	Static collapse strength (kgf)	Ratio of static collapse strength
Article X	3	4000	1.00
Article Y	3	3250	0.81
Article Z	3	4250	1.06

The static collapse toughness was lower in the carbonitrided Article Y than in the normally quenched article X. In comparison, Article Z of the present invention has a static collapse toughness that is higher than Article Y and is comparable to Article X.

(5) Dimensional change over time

The articles were kept at 130°C for 500 hours and the dimensional change was determined. The results are shown in Table 7, along with the surface hardness and the retained austenite content (at a depth of 50 μM).

(Table 7)

Materials	Test number	Surface hardness (HRC)	Retained γ (%)	Dimensional change ($x10^{-5}$)	Ratio of dimensional change
Article X	3	63.0	11	23	1.0
Article Y	3	64.0	27	41	1.8
Article Z	3	62.1	15	28	1.2

The results indicate that Article Z of the present invention underwent a 70% or less dimensional change with respect to Article Y containing more retained austenite.

(6) Rolling life test in the presence of foreign particles

A ball bearing 6206 was used to determine the rolling fatigue life in the presence of a predetermined amount of standard foreign particles. The test condition and the test results are shown in Tables 8 and 9, respectively.

(Table 8)

Load	Fr = 6.86 kN
Contact surface pressure	Pmax = 3.2 GPa
Rotation speed	2000 rpm
Lubricant	Turbine 56 oil bath
Amount of foreign particles	0.4 g/1000 cc
Foreign particles	Particle size 100 to 180 μm, hardness Hv 800

(Table 9)

Materials	L_{10} life (h)	Ratio of L_{10}
Article X	23.5	1.0
Article Y	40.8	1.7
Article Z	37.7	1.6

The conventionally carbonitrided Article Y has a 1.7 times longer rolling fatigue life than Article X, and Article Z of the present invention has a 1.6 times longer life than Article X. Article Z of the present invention contained less retained austenite than Article Y of Comparative Example, but nonetheless achieved equally long life because of nitrogen penetration and fine microstructure.

These results suggest that Article Z of the present invention meets all of the three requirements that have been difficult to achieve by the conventional carbonitriding process: the long rolling fatigue life, the increased crack resistance, and the decreased dimensional change over time.

(Example III)

Table 10 shows the results of a test conducted to determine the relationship between the nitrogen content and the rolling life in the presence of foreign particles. Comparative Example 1 corresponds to a sample quenched by a standard technique and Comparative Example 2 corresponds to a sample carbonitrided by a standard technique. Comparative Example 3 corresponds to a sample that was treated by the same process as in Example of the present invention except that it contains higher level of nitrogen. Testing

conditions are as follows:

Sample bearing: Cone-shaped roller bearing 30206 (The inner ring, outer ring, and rollers are each made of a steel alloyed with 1.2wt% C, 1.0wt% Si, 0.5wt% Mn, 1.0wt% Ni, and 1.5wt% Cr).

Radial load = 17.64 kN

Axial load = 1.47 kN

Rotation speed = 2000 rpm

Amount of hard foreign particles = 1 g/L

(Table 10)

No.	Nitrogen content (%)	Retained austenite (%)	Hardness (Hv)	Rolling life in the presence of foreign particles (h)	Note
1	0.11	14	730	370	Example 1
2	0.16	19	735	400	Example 2
3	0.18	21	730	390	Example 3
4	0.32	22	730	410	Example 4
5	0.61	28	705	440	Example 5
6	0	9	750	60	Comparative Example 1
7	0.32	27	700	121	Comparative Example 2
8	0.72	35	680	98	Comparative Example 3

As shown in Table 10, the rolling life in the presence of foreign particles is substantially in proportion to the nitrogen content in each of Examples 1 through 5. The upper limit of the nitrogen content is preferably 0.7 since Comparative Example 3 with a nitrogen content of 0.72 had a significantly shorter rolling life in the presence of foreign particles.

The above-described embodiments are only illustrative and should not be construed as a limitation of the invention. The scope of the invention should not be determined by the foregoing description, but by the appended claims, which are intended to encompass all equivalents and modifications made within the scope of the invention.